Direct evidence of efficient cosmic ray acceleration and magnetic field amplification in Cassiopeia A

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Abstract. It is shown that the nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) describes the shell-type nonthermal X-ray morphology of Cas A, obtained in Chandra observations, in a satisfactory way. The set of empirical parameters, like distance, source size and total energy release, is the same which reproduces the dynamical properties of the SNR and the spectral characteristics of the emission produced by CRs. The extremely small spatial scales in the observed morphological structures at hard X-ray energies are due to a large effective magnetic field $B_d \sim 500\,\mu$G in the interior which is at the same time not only required but also sufficient to achieve the excellent agreement between the spatially integrated radio and X-ray synchrotron spectra and their calculated form. The only reasonably thinkable condition for the production of such a large effective field strength is a very efficiently accelerated nuclear CR component. Therefore the Chandra data confirm first of all the inference that Cas A indeed accelerates nuclear CRs with the high efficiency required for Cas A to be considered as a member of the main class of Galactic CR sources and, secondly, that the nonlinear kinetic theory of CR acceleration in SNRs is a reliable method to determine the magnetic field value in SNRs.

Key words. cosmic rays, shock acceleration, nonthermal emission, supernova remnants; individual: Cas A

1. Introduction

Supernova remnants (SNRs) are the main sources of energy for the Interstellar Medium (ISM). They control the physical state of the ISM, and that presumably includes the nonthermal component of Interstellar matter, often called the Galactic Cosmic Rays (CRs). Quantitative analysis of the SNR dynamics and its energetic particle production requires the determination of the effective magnetic field in SNRs. For this we note that the magnetic field decisively influences the acceleration of CRs and their subsequent dynamics in SNRs. In the following we shall present evidence for the case of Cassiopeia A (Cas A) that the nonlinear kinetic theory for CR acceleration in SNRs (Berezhko et al. 1996; Berezhko & Völk 1997; 2000) does not only satisfactorily explain the observed SNR dynamics and the properties of the nonthermal emission, but that it also permits to determine the value of the effective magnetic field in SNRs, as already demonstrated for the case of SN 1006 (Berezhko et al. 2002; 2003a).

The existence of a powerful population of relativistic particles in SNRs is known from their nonthermal radiation. For some SNRs this emission is detected in a very wide range from the radio to the γ-ray band. Cas A represents such an example.

It is a shell-type SNR, and a bright source of synchrotron radiation observed from radio waves (e.g. Baars et al. 1977) to hard X-rays (Allen et al. 1997). These emissions are direct evidence for the existence of a large number of relativistic electrons presumably accelerated at the shock, with energies reaching about 10 TeV. Direct experimental knowledge of nuclear CR production can only be obtained by high energy γ-ray measurements. If protons are efficiently accelerated in Cas A, then the π^0-decay γ-ray spectrum as a result of inelastic collisions with the background nuclei must extend beyond 1 TeV with a hard power-law spectrum. The detection of a corresponding if weak signal in TeV γ-rays has been indeed reported by the HEGRA collaboration (Aharonian et al. 2001).

According to the analysis by Borkowski et al. (1996) which is consistent with the observed dynamics of Cas A, the supernova shock expands into a non-uniform circumstellar medium strongly modified by the intense progenitor star wind. This circumstellar environment consists of a tenuous inner bubble, created by the Wolf-Rayet wind, a dense shell of swept-up slow Red Supergiant (RSG) wind material, and a subsequent unperturbed RSG wind. The medium further out is not relevant here. Since the shock has already passed through the dense shell and has swept up a mass of about $5M_\odot$ (Favata et al. 1997), a detectable π^0-decay γ-ray flux is to be expected. Recently

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Chevalier & Oishi (2003) have argued that a Wolf-Rayet phase and the corresponding modification of the preexisting RSG wind is not required. To reach a final conclusion about this important issue a detailed dynamical and kinetic consideration has to be made, similar to the one contained in our previous paper (Berezhko et al. 2003b). At the moment we can only say that the global characteristics of nonthermal radiation of Cas A are expected to be not sensitive to these details of the structure of circumstellar medium, because they are mainly determined by the total amount of the swept up gas and the magnetic field value in the remnant. Since the observed hard X-ray synchrotron emission of Cas A comes from the thin region near the current SN shock position, the properties of this radiation are not expected to be very sensitive to the previous history of the SNR evolution. Here we use our model (Berezhko et al. 2003b) which agrees with all previous data, leaving the question about the role of Wolf-Rayet stage for future scrutiny, and test its consistency with the hard X-ray morphology.

Comparing the nonthermal radio and X-ray synchrotron data with the calculated spectrum of the energetic electrons, Berezhko et al. (2003b) have inferred that the existing data require very efficient acceleration of *CR nuclei* at the SNR blast wave which has converted already several percent of the initial SNR energy content into nuclear CR energy despite the necessity of renormalization of the overall nuclear CR content due to the nonuniform injection of suprathermal ions (Völk et al. 2003). At the same time a large interior magnetic field strength $B_d \approx 500\mu G$ is required. The large value of B_d is expected and possible in this case, using the spatially integrated radio and X-ray synchrotron spectra to empirically determine the effective magnetic field strength and the injection rate in the theory (see also Völk 2003).

In fact there are very recent measurements of details of the X-ray morphology of Cas A with the Chandra telescope by Vink & Laming (2003). These authors have used the detailed Chandra morphology to estimate the magnetic field strength by assuming the small spatial X-ray scale to be determined by postshock synchrotron losses. Our aim is to show that the actual B-field strength coincides with that inferred from the radio spectrum and nonlinear acceleration theory. We confirm that the field is indeed amplified in Cas A, although it turns out that the actual value is significantly larger than estimated by Vink & Laming (2003).

2. Results and discussion

Compared with SN 1006 which exploded into an essentially uniform ISM, Cas A is a very different and much more complex object. The dynamics of the SN shock and the major fraction of the emission produced by accelerated CRs are predominantly determined by the parameters of the swept-up RSG shell. They depend less sensitively on the parameters of the medium near the current shock position since that presumably consists of free RSG wind material and contains little mass. Nevertheless, since the required magnetic field in the interior downstream of the shock is so large that it strongly influences the energy spectrum of the CR electrons as a result of their synchrotron losses (Berezhko et al. 2003b), the hard X-ray synchrotron emission

should come predominantly from the relatively thin postshock region, because deeper inside the remnant the upper cutoff energy of CR electrons becomes too low. Therefore one would expect that the nonlinear kinetic theory should not only reproduce the spectral characteristics of Cas A in a satisfactory way, but should also be able to explain the observed fine structure of the nonthermal emission in hard X-rays.

For the comparison with the Chandra data we shall not present the details of our model. They have already been described in the above paper (Berezhko et al. 2003b). In order to give a clear interpretation and simple estimate of the spatial variation of the synchrotron emission near the SNR shock we shall use some simple analytical approximations, extending the discussion of SN 1006 (Berezhko et al. 2003a). As a second step we shall make a comparison of the Chandra data with the results of the nonlinear theory.

It was shown (Berezhko et al. 2003a) that due to the strong synchrotron losses the very energetic electrons occupy only a thin region behind the shock of thickness

$$l_2^{-1} = (2l_{d2})^{-1}(\sqrt{1 + 4l_{d2}/l_{c2}} - 1), \tag{1}$$

where $l_d(p) = \kappa(p)/u$ and $l_c(p) = \tau(p)u$ are the diffusive and convective length scales respectively, $\tau(p) = 9m_e^2c^2/(4r_0^2B^2p)$, is the synchrotron loss time, m_e is the electron mass, r_0 denotes the classical electron radius, B is the effective magnetic field strength, $\kappa(p) = \rho_B v/3$ is CR diffusion coefficient, and $\rho_B(p)$, p and v are the particle gyroradius, momentum and velocity, respectively. In addition $u_2 = V_s/\sigma$ is the downstream plasma speed relative to the shock front, V_s is the shock speed, and σ is the total shock compression ratio.

Depending upon the ratio l_d/l_c we have two different extreme cases. For electron momenta p corresponding to $l_c \gg 4l_d$ (weak losses) we have $l_2 = l_c$. In this case the loss time τ is much larger than the acceleration time $\tau_{acc} \sim \kappa/u^2$ and therefore the losses do not influence the electron spectrum during their acceleration. The electron spectrum has a power law character up to a cutoff momentum $p_{max} > p$, which exceeds the considered momentum p. Later on, the losses in the downstream region lead to a decrease of the cutoff momentum so that at the distance $r = R_s - l_c$ it drops to the value $p_{max}(r) = p$. Here R_s is the shock radius. In the opposite extreme case of strong losses $l_c \ll 4l_d$, we have $l_2 = \sqrt{\kappa_2\tau_2}$. which is in fact independent of momentum if particle diffusion proceeds in the Bohm limit. In this case losses become significant already during the electron acceleration and therefore the cutoff momentum p_{max} is lower than p, so that the corresponding electrons belong to the exponential tail of the distribution. Since the nonthermal X-ray emission of Cas A belongs to the steep tail of the synchrotron spectrum, Eq.(1) suggests that $l_c \ll l_d$ for the radiating electrons.

Since the synchrotron data are given in terms of the emission frequency ν, it is useful to rewrite Eq.(1), taking into account the approximate relation $\nu \propto Bp^2$:

$$l_2 = \sqrt{\kappa_2\tau_2}/(\sqrt{1 + \delta^2} - \delta), \tag{2}$$

where

$$\delta^2 = l_{c2}/(4l_{d2}) = 0.12[c/(r_0\nu)][V_s/(\sigma c)]^2. \tag{3}$$

We then have the situation that the synchrotron emissivity $q_\nu(\epsilon_\nu, r)$ is everywhere close to zero except for a thin radial region of thickness $\Delta r \sim l_2$ just behind the SN shock, since the emissivity from the upstream region $r > R_s$ is insignificant.

In projection along the line of sight, the radial emissivity profile determines the remnant's surface brightness J_ν. For the X-ray energy ϵ_ν it has the form

$$J_\nu(\epsilon_\nu, \rho) = 2 \int_a^0 dx q_\nu(\epsilon_\nu, r = \sqrt{\rho^2 + x^2}), \tag{4}$$

where ρ is the distance between the center of the remnant and the line of sight. In the case of a spherical shock $a = -\sqrt{R_s^2 - \rho^2}$.

To estimate the shape of the expected profile $J_\nu(\rho)$ one can consider the simple case, when the emissivity has a form

$$q_\nu(\epsilon_\nu, r) = q_2(\epsilon_\nu) \exp[(r - R_s)/l_2] \tag{5}$$

for $r \leq R_s$. In the case of interest, $l_2 \ll R_s$, the main contribution to the integral (4) comes from the thin regions near the boundary $x = a$. To perform the integration along the line of sight one can therefore expand the quantity $r = \sqrt{\rho^2 + x^2}$ in Eq.(5) in powers of $x - a$ up to the second order term which results in:

$$J_\nu = \frac{2q_2 R_s l_2}{\sqrt{R_s^2 - \rho^2}} \left\{ 1 - \frac{R_s^2 - 2\rho^2}{R_s^2 z} - \right.$$
$$\left. - e^{-z} \left[1 - \frac{R_s^2 - 2\rho^2}{R_s^2 z} + \frac{(z+2)}{2} \left(\frac{2\rho^2 - R_s^2}{R_s^2} \right) \right] \right\}, \tag{6}$$

where $z = (R_s^2 - \rho^2)/(R_s l_2)$. This approximate expression is accurate to about one percent for the case of a small thickness of the emission layer $l_2 \ll 0.1 R_s$. As it is clear from this expression the distant observer will see the profile $J_\nu(\rho)$ which, going from large distances to the center of the SNR, starts at $\rho = R_s$, reaches its peak value $J_{max} = 2q_2 \sqrt{R_s^2 - \rho_m^2}$ at $\rho_m \approx R_s - 0.85 l_2$ and smoothly drops to $J_{min} = 2l_2 q_2$ at the SNR center $\rho = 0$. Therefore the outer scale $L_1 \approx l_2/2$ characterizes the emission profile at $\rho > \rho_m$, whereas for the inner scale, which characterizes the profile at $\rho < \rho_m$, we have $L_2 \approx 13 L_1$. This means that the width $L = L_1 + L_2 \approx 7 l_2$ of the observed brightness profile $J_\nu(\rho)$ is always appreciably wider than the width l_2 of the emissivity layer $q_\nu(r)$, simply due to the geometry of the system.

According to (2) the downstream magnetic field B_d is

$$B_d = [3m_e^2 c^4/(4er_0^2 l_2^2)]^{1/3} (\sqrt{1 + \delta^2} - \delta)^{-2/3}. \tag{7}$$

The case of strong losses $l_c \ll 4l_d$ corresponds to $\delta = 0$. According to Vink & Laming (2003) the total thickness of the observed profile at $\epsilon_\nu > 2.7$ keV is as small as $1.5''$. However, following the above consideration, only the small fraction $1.5''/7 \approx 0.22''$ corresponds to the thickness of the downstream emission region l_2. For a distance $d = 3.4$ kpc and an angular radius of $2.6'$ for Cas A this gives $l_2 \approx 1.1 \times 10^{16}$ cm. In the case of strong losses ($\delta = 0$) $B_d \approx 470\,\mu$G, independently of synchrotron energy and shock speed. For $V_s = 3000$ km/s and $\sigma = 6$, corresponding to the overall nonlinear model
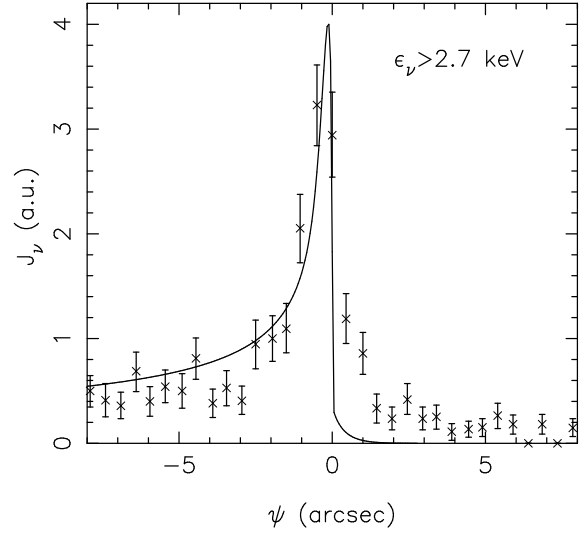
Fig. 1. The X-ray emissivity for X-ray energies $2.7 < \epsilon_\nu < 9$ keV as a function of angular radial distance. The Chandra measurements are shown (Vink & Laming 2003).

(Berezhko et al. 2003b), $\delta^2 = 0.054$ resulting in $B_d \approx 550\,\mu$G. For a larger shock speed $V_s = 5000$ km/s, as derived from X-ray measurements and used by Vink & Laming, we have $\delta^2 = 0.15$ and $B_d \approx 610\,\mu$G.

The corresponding magnetic field value is by a factor of about five larger than estimated by Vink & Laming (2003). There are two reasons for such a large discrepancy (i) only a small part of the observed profile width L corresponds to the thickness l_2 of the emission region (ii) the correct formula (1), cf. Völk et al. (1981), implies $l_{c2} < l_2$. Using $l_{c2} = L$, as was done by Vink & Laming, therefore doubly underestimates B_d, since $l_{c2} \propto B_d^{-2}$.

The numerically calculated brightness profile $J_\nu(\rho) = \int_{\epsilon_1}^{\infty} d\epsilon_\nu J_\nu(\epsilon_\nu, \rho)$ for the X-ray energy $\epsilon_\nu > \epsilon_1 = 2.7$ keV is shown in Fig.1. The sharpest experimental X-ray brightness profiles obtained by the Chandra observers (Vink & Laming 2003) are shown as a function of angular distance $\psi = 2.6 \times 60 (\rho - R_s)/R_s$ in arcseconds, taking into account that the angular radial size of Cas A is $2.6'$. Since the absolute values of the measurements are not known, the theoretical profile is normalized so as to obtain the best fit to the experimental profile. The very sharp part on the right side of the calculated profile $J_\nu(\psi)$ corresponds to the shock front position $\rho = R_s$. Compared with Vink & Laming (2003) all experimental points are shifted by $\Delta\psi = 0.3''$ to the left. One can see that the experimental values agree quite well with our calculations, which yielded a post-shock value of the magnetic field strength at the current evolutionary epoch (see Berezhko et al. 2003b) of $B_d = 480\,\mu$G. Taking into account that the Chandra angular resolution is $0.5''$ we conclude that the actual downstream magnetic field in Cas A is indeed $B_d \approx 500\,\mu$G with an uncertainty of about 30% which encompasses the above simple estimates of the local field.

There are a number of reasons for a broadening of the observed profile, compared with the ideal case of a spherical shell. First of all, it is clear from the observations that the actual shock

front deviates from a strictly spherical form. The wavy shape of the shock front can be produced as the result of small scale density inhomogeneities of the ambient ISM. Any small-scale distortion of the spherical emission shell leads to a broadening of the observed brightness profile. This explains why the observed X-ray radial profile is slightly broader than the theoretical profile (see Fig.1). Therefore it is hard to believe that the actual magnetic field in Cas A could be significantly lower than the above value.

Since at the current epoch the supernova shock propagates through the free RSG wind, where the required effective magnetic field would be so strong that the Alfvén speed is $c_a \approx 160$ km/s (Berezhko et al. 2003b), this field exceeds the preexisting wind field by at least an order of magnitude, because the wind should presumably be superalfvenic, that is $c_a < V_w$, where $V_w \sim 10$ km/s is the RSG wind velocity. From this argument, the required strong downstream magnetic field is inevitably the result of considerable amplification near the supernova shock. As argued for the case of SN 1006 (Berezhko et al. 2003a) such a strong magnetic field amplification can only be produced nonlinearly by a very efficiently accelerated *nuclear CR component*. In this case their number, consistent with all existing data, is so high that they are able to strongly excite magnetohydrodynamic waves, and thus to amplify the magnetic field, and at the same time to permit efficient CR scattering on all scales, approaching the Bohm limit (Bell & Lucek 2001). The same large effective magnetic field is required by the comparison of our selfconsistent theory with the synchrotron observations.

For such a high downstream magnetic field $B_d \approx 0.5$ mG, which leads to strong synchrotron losses of the CR electron component, the leptonic contribution to the TeV γ-ray emission is so small that it is far below the detected HEGRA flux (Berezhko et al. 2003b).

3. Summary

We conclude that the Chandra data confirm the magnetic field amplification and the very efficient acceleration of nuclear CRs in Cas A, predicted by Berezhko et al. (2003b). This efficiency is consistent with the requirements for the Galactic CR energy budget. At the same time, together with SN 1006 (Berezhko et al. 2002; 2003a) this is now a second – and astrophysically very different – case, where the prediction of the nonlinear kinetic model for CR acceleration in SNRs is fully confirmed experimentally. Therefore we conclude that this theory is not only able to describe the CR dynamics and acceleration in SNRs, but that it constitutes in addition a reliable method to quantitatively determine the effective magnetic field strength which is produced in the acceleration process.

Since our model uses the Bohm diffusion of CRs, which is consistent with the field amplification picture, one can consider the consistency of the magnetic field values required to explain the global properties of the synchrotron emission on the one hand (Berezhko et al. 2003b), and to reproduce the fine structure of the X-ray radiation on the other as observational support for the Bohm limit of CR diffusion near the strong SNR shock.

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